Developing screw piles for offshore renewable energy application

Brown, Michael J.; Davidson, Craig; Cerfontaine, Benjamin; Ciantia, Matteo; Knappett, Jonathan; Brennan, Andrew

Published in:
Advances in Offshore Geotechnics

DOI:
10.1007/978-981-15-6832-9_5

Publication date:
2020

Citation for published version (APA):
Brown, M. J., Davidson, C., Cerfontaine, B., Ciantia, M., Knappett, J., & Brennan, A. (2020). Developing screw piles for offshore renewable energy application. In S. Haldar, S. Patra, & R. K. Ghanekar (Eds.), *Advances in Offshore Geotechnics: Proceedings of ISOG2019* (pp. 101-119). (Lecture Notes in Civil Engineering; Vol. 92). Springer . https://doi.org/10.1007/978-981-15-6832-9_5

Developing screw piles for offshore renewable energy application

Michael J Brown, Craig Davidson, Benjamin Cerfontaine, Matteo Ciantia, Jonathan Knappett & Andrew Brennan
University of Dundee, Dundee, Scotland, UK

ABSTRACT
This paper details the work undertaken at the University of Dundee in the last 5 years to develop understanding of screw piles to allow them to be deployed offshore as an alternative foundation type to driven piles used in jacket structures. This has been prompted by several UK and European funded research initiatives to develop silent foundation techniques to mitigate affects on marine mammals and other animals. Current mitigation systems also have significant associated costs and questionable environmental credentials. Prior to starting this work, it was recognized that development would not progress unless the ability to predict installation requirements did not form an early part of the research investigation. This then led to investigation of methods to reduce installation requirements and development of new design approaches for the required new screw pile geometries. This paper details the progress of these investigations which are still ongoing.

1 INTRODUCTION

Screw piles or screw anchors have been recognized as having the potential to develop from there small current onshore size with low pile central core diameters (D_c) and larger helix diameters (D_h).This development for offshore application will require the upscaling of size and general geometry to carry significantly greater loads than they are currently used for onshore as well as a more complex loading regimes with combinations of tension and compressive loading (Davidson et al, 2018), lateral loading (Al-Baghdadi. et al, 2015 & 2017, Pavan Kumar et al. 2019) and cyclic loading (Newgard et al. 2019, Schiavon et al. 2019). This may be as a result of use as anchors in aquaculture or future floating offshore wind or as alternative foundations to driven piles in jacket structures.

The use of screw piles in jacket structures offshore is being motivated by the strict requirements to mitigate or minimize noise during installation of wind farms in Europe (Koschinski and Lüdemann, 2013) with similar restrictions being imposed in emerging wind developments in other areas of the world (Huisman et al, 2020). This could result in costs as high as $1M US for noise mitigation per wind turbine jacket structure. As well as direct costs the environmental credentials of noise mitigation systems may be called into question with the need for constant DP vessel presence and compressors operation resulting in significant fuel use to create bubble curtains.

This paper outlines some of the work undertaken at the University of Dundee which has been designed to bring the use of large screw piles in an offshore setting closer to a realistic prospect. Investigation to date has focused on sands only.

1.1 Historical research on screw based piling systems at the University of Dundee

Research on various forms of screw piles in sand has been ongoing at the University of Dundee since 2007. Initially this was for a form of cast in-situ screw pile referred to as the continuous helical displacement pile or CHD (Knappett & Craig, 2019). This investigation focused on the development of compressive capacity calculation techniques (Jeffrey et al, 2016) and verification of operational or effective pile diameters through 1g testing (as centrifuge refurbishment for earthquake capabilities were underway, Brennan et al, 2014). Based upon these works and field database investigation a method of simulating CHD installation effects was also developed for Plaxis 2D to allow this process to be simulated numerically by industry (Knappett et al, 2013).

To undertake these works 1g equipment was developed that allowed pitch matched or perfect installation (Lutenegger 2019) to occur with the ability to inject grout on removal of the CHD bullet. This system also included measurements of axial loads as well using a dedicated torque cell during installation and injection (Jeffrey, 2012).

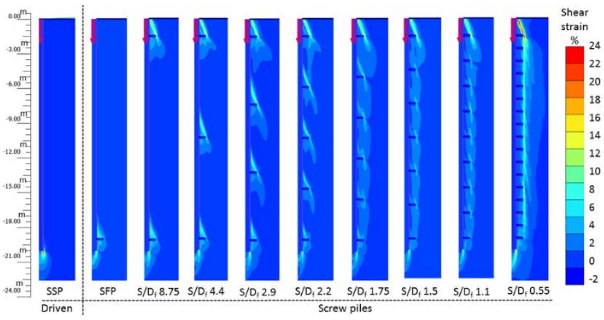

Figure 1. FEA Study of optimization of helix spacing for compressive loading (Al-Baghdadi, 2018).

This equipment was then utilized over several years to service undergraduate and MSc projects but in a simpler form to install solid steel screw piles. This was done to service the ever-present need for student projects. Often these screw piles were fabricated in a modular manner to allow various elements of behaviour to be investigated. Projects looked at a range of things

This is a post-peer-review, pre-copyedit version of an article published in *Advances in Offshore Geotechnics: Proceedings of ISOG2019*. The final authenticated version is available online at: http://dx.doi.org/10.1007/978-981-15-6832-9_5.

including cyclic performance, optimizing helix spacing (*s/D*) for compressive and tensile performance (Knappett et al, 2014) and inclined loading for use as offshore or aquaculture anchoring systems (Caton, 2016 & Horvath, 2018).

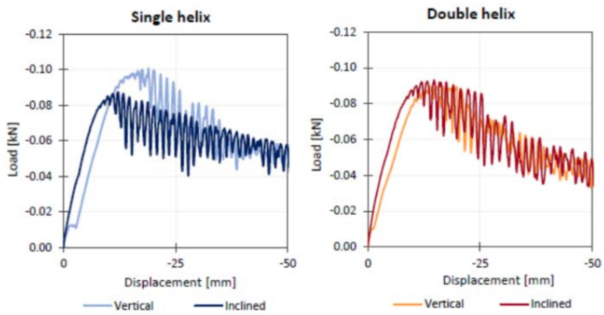

Figure 2. 1g model testing of vertical and inclined screw pile anchors (Horvath, 2018).

The first full time study of screw piles as replacement for driven plies for offshore wind jacket structures began in 2013 and was undertaken by Al-Baghdadi. Al-Baghdadi (Al-Baghdadi, 2018) wanted to undertake numerical modelling of screw piles and had an interest in renewable energy foundations. With a need for validation of the numerical work (as there were little useful detailed field test case studies in existence for installation requirements) it was also decided to undertake scaled physical modelling at appropriate stress levels. This required the development of a bespoke centrifuge rig with the additional requirement that installation and testing could be undertaken all at an appropriate g level as many previous studies installed at g, or partially installed at 1g and tested at g, or partially installed at 1g and g (Al-Baghdadi, et al, 2016 and Davidson et al, 2018).

2 AREAS OF SCREW PILE DEVELOPMENT

2.1 Structural and load carrying capacity

2.1.1 Lateral loading and capacity

From an early stage of investigation of screw piles for offshore renewable energy development it was obvious that considerable upscaling of the currently used onshore piles was required with an increase in helix diameter to allow increased tensile and compressive capacity as well as increased core or steel cross-sectional area to allow the pile the large lateral capacity required in offshore applications. Initially Al-Baghdadi (2018) focused on axial compressive load performance in sands as this part of screw pile behavior had seen little attention as they are normally designed to be used in tension. This resulted in a multi helix pile design similar to that shown in Figure 1 where the helix plates were spaced between 2-3 D_h for optimal capacity whilst inducing soil-soil shear. Al-Baghdadi (2018) also considered the optimum core (D_c) to helix diameter ratio (D_h) so that piles could still perform well (also approximately 2) with less stick out of the helix plates to improve offshore handling and vessel storage.

Then attention turned to attempts to increase lateral performance firstly through the use of near surface helix plates (Al-Baghdadi, et al, 2015). This seemed a viable option initially based upon FEA modelling but it was found that although the lateral resistance with large near surface plates could be increased by up to 22% when compared to a straight shafted pile the helix plate had to be placed very close to the seabed surface for greatest efficiency (Figure 4). On the grounds that this near seabed zone would be subjected to scour this proposed method of increasing lateral capacity seems unlikely to be adopted without appropriate scour protection.

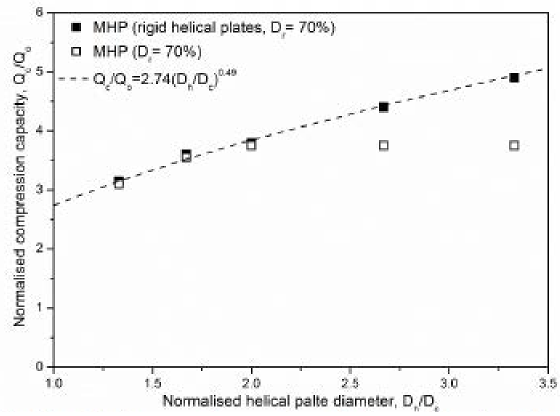

Figure 3. Effect of varying helix to core diameter ratio (Al-Baghdadi, 2018).

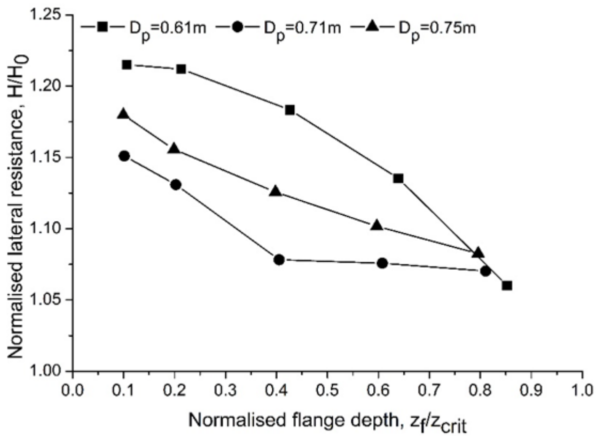

Figure 4 Results of 3D Plaxis simulation to identify the potential of near surface helix plates ability to deal with lateral loading demands (Al-Baghdadi, 2018).

Further investigation of combined lateral and vertical loading (both compression and tension) affects were modelled using Plaxis 3D validated against a number of field studies (although field study case histories for lateral loading are limited in the literature, Sakr, 2010 & Zhang, 1999). Similar combined loading was investigated by Karthigeyan (2008). The study by Al-Baghdadi et al. (2017a) showed that the lateral performance of both straight shafted and screw piles is enhanced under compressive vertical loading, with greater enhancement for screw piles. For both pile types the lateral performance degraded under vertical tension loading (below a zero vertical load situation). Interrogation of the radial stresses and earth pressures mobilised during modelling suggested that the presence of screw pile helical plates has the potential to increase the vertical compressive stresses below the helical plates and the resulting radial stresses, which in turn increases lateral pile resistance and vertical capacity of the pile core. Screw piles potentially offer good performance when used in jacket or tripod arrangements where the horizontal loading can be shared and where moments acting on the jacket can be carried principally in axial tension/compression, superimposed on the static self weight. These will be particularly effective if the screw piles can remain (just) in compression under maximum environmental horizontal loads. The main drawback of the enhanced lateral capacity of screw piles with increasing vertical compressive loads is that greater bending moment is induced in the core of the pile. This implies a need to carefully consider the central core to ensure it has sufficient moment capacity so as not to yield under the combined effects of vertical and lateral loading.

2.1.2 Axial capacity

Although a multiple helix pile configuration may be logical where axial compressive capacity is required and helix spacing can be optimized to induce soil-soil shearing between the helix plates the same cannot be said for axial tension. As has been shown by many previous authors the axial tensile capacity is dominated by the either a shallow (uplifting wedge from top surface of the plate to the seabed) or a deep mechanism (flow around the helix plate or a local bearing capacity mechanism). This behaviour is dependent on the soils density and the ratio of the depth of the upper plate (*H)* to the diameter of the helix (Figure 5).

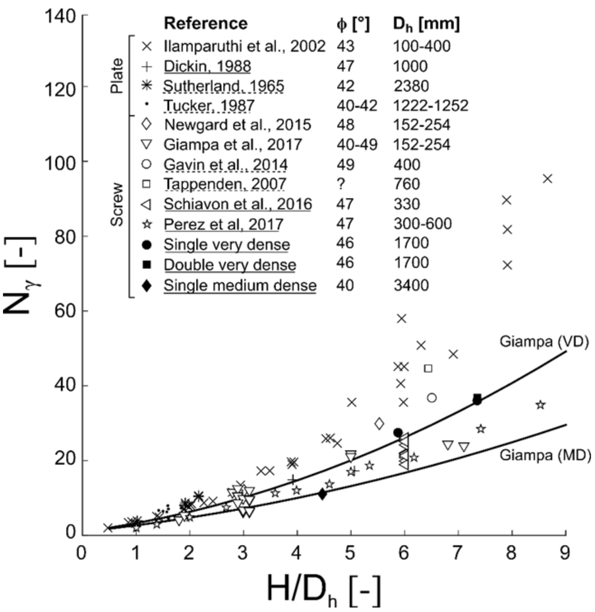

Figure 5 Variation of uplift resistance with increasing depth for shallow mechanisms.

Figure 5 only considers the shallow mechanism behaviour where transition may occur at H/D = 7 to 9. Whilst undertaking numerical modeling (Cerfontaine, et al, 2019a) of this uplift process to understand shallow mechanism controls it was found that the position of the upper helix (where multiple helices were installed) tended to determine the initiation point for any uplifting wedge (Cerfontaine, et al, 2019a). Based upon this finding it would suggest that for a pile installed to a "shallow" level (which may be relatively deep for a pile with a large diameter helix plate and *H/D*) a single helix plate may be superior in tension to a multi helix design which was contrary to the findings or direction of investigation for early compressive performance studies by Al-Baghdadi (2018).

This work also showed that the failure plane that the shallow mechanism followed was defined by the dilation angle of the sand as found in other applications such as the uplifting of pipelines. It also suggested how existing analytical techniques could be improved to include the findings from FE analysis to give better predictions of screw pile uplift capacity (Cerfontaine et al, 2020).

At the same time as undertaking these numerical studies Davidson et al (2018a) began centrifuge testing on a series of piles designed to have the structural and load carrying capabilities to support a large jacket and wind turbine system designed to be installed in 80m of water depth. This resulted in a pile that would be required to carry 6.28MN in lateral loading, 26.14MN tensile loading and 34.85MN compressive loading. The resulting piles were designed based upon classic onshore screw pile methodologies: tensile resistance from the multi-helix method in Das & Shukla (2013); cylindrical shear method in Perko (2009) for compressive capacity; and analytical methods in Fleming et al. (2008) for the lateral capacity.

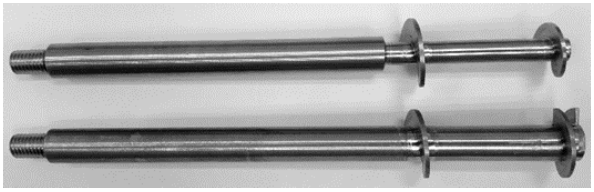

Figure 6. Examples of the 80th scale model piles designed to operate in very dense soil. The upper pile is the optimised pile.

The first design had uniform core and helix dimensions, while the second (upper), optimized design, had reduced core and bottom helix diameters (Figure 6 and Table 1) which were designed to give reduced installation requirements whilst maintaining axial and lateral capacity requirements. Santos Filho et al. (2014) demonstrated a substantial reduction in installation torque of small diameter onshore screw piles with a reduced core diameter over designs with a uniform core diameter.

It is clear in considering the piles in Figure 6 that at this stage the findings on limiting uplift performance by the upper helix were unknown as the pile had two helices although a single helix pile was also tested at the same time of similar length.

Results from compressive and tension capacity testing showed that the existing design techniques for tension and compressive capacity were not able to capture the behavior of the piles sized for offshore deployment and performed particularly badly (overprediction of true capacity 34-77%) in the case of tensile capacity predictions (Davidson et al, 2020).Much better prediction of compressive capacity was achieved using the approaches developed by Jeffrey et al. (2016)

and in tension lower uplift factors as per Figure 5 coupled with the use of the uplifting failure wedge defined by the dilation angle of the sand.

Table 1. Screw pile dimensions in meters at prototype scale (mm at model scale), See Figure 6.

Parameter		~~Standard~~ ~~,~~ ~~u~~Uniform screw pile	Optimized screw pile
Length, *L*		13 (162.5)	
Core diameter	Upper	0.88 (11)	
	Lower	0.88 (11)	0.60 (8)
Helix diameter,	Upper	1.70 (21.25)	
	Lower	1.70 (21.25)	1.34 (16.75)
Pitch, *p*	Upper Lower	0.56 (7)	0.56 (7.5)
Thickness, *t*	Upper Lower	0.11 (1.4)	0.11 (1.4)
S/D_h		2	2

Historically screw pile capacity (*Q*) (in tension or compression) has been linked to the torque (*T*) required to install the piles via a torque factor (*K*):

$$Q = KT \qquad [1]$$

$$K_t = 1433/D_c^{0.92} \qquad [2]$$

Where K is a torque correlation factor which maybe selected based upon the core diameter of the screw pile (Eq. 2) (D_c) by Perko (2009). This approach though shows significant scatter in the selection of the *K* value even over the limited core diameters used onshore. Perko (2009) recommended that similar K values could be used in both tension and compression but this advice would seem problematic as it does not recognize in tension for instance that the uplift mechanism may vary between a deep and shallow mechanism and torque measurements would not be influenced by this in-service behavior. For instance, an offshore pile geometry is more likely to be operating in a shallow mechanism due to its large helix diameter (i.e. *H/D*) whereas a small diameter onshore pile may be more likely to operate in a deep mechanism mode.

Davidson et al. (2020) showed that adopting the approach for tensile capacity prediction resulted in overproduction of 283%. Lutenegger (2019) highlights that correlations of torque to capacity are often assumed to be the same whether one or two helices are included (i.e. the inclusion of additional helix plates is ignored) and goes onto show that the torque encountered during installation is also affected by the pitch of a helix plate, while the capacity is unaffected. Thus, non-unique values of K_t can be observed for screw piles with the same shaft diameter. It is also assumed that *K* is unaffected by relative density and that piles are always installed in the same manner (pitch matched) which seems unlikely based upon the apparent vertical force requirements which may not be encountered in the field (based upon existing rig reaction mass) and that in-service performance is unaffected by installation approaches.

2.2 Installation requirements

The initial centrifuge testing by Al-Baghdadi (2018) and Davidson et al. (2018a) highlighted at an early stage that significant torques were required for installation (Figure 7) and thus the need to experiment with reduced cross-sectional area piles (Figure 6) as the torque required is a function of the piles surface area.

Figure 7 highlights that there is the potential to reduce torque in a limited fashion but Davidson et al. (2020) found that .the optimized pile design did not perform in tension or compression as expected and gave lower capacities than the non-optimized form.

What was possibly more concerning was that for the pitch matched (or perfect) installation adopted here, and as per common guidance on installing screw piles to minimize disturbance and ensure in-service capacity, the vertical forces (or crowd force) measured during installation were also very high. Possibly to the level where they could not be installed, or very significant reaction force would be needed which would be difficult to create in an offshore setting. This vertical force requirement also came as somewhat of a surprise as crowd force is not normally measured during onshore screw pile operations and onshore rigs may have high torque capacity but relatively low self-weight making it appear impossible to supply the apparent vertical forces required for installation. This suggests that screw piles may not be installed in the pitch matched or perfect installation procedure recommended. Again, this is difficult to verify for onshore installation as only installation torque is normally measured directly (or indirectly). Records of advance rates and rotation rates are not normally made and rigs do not capture this information automatically.

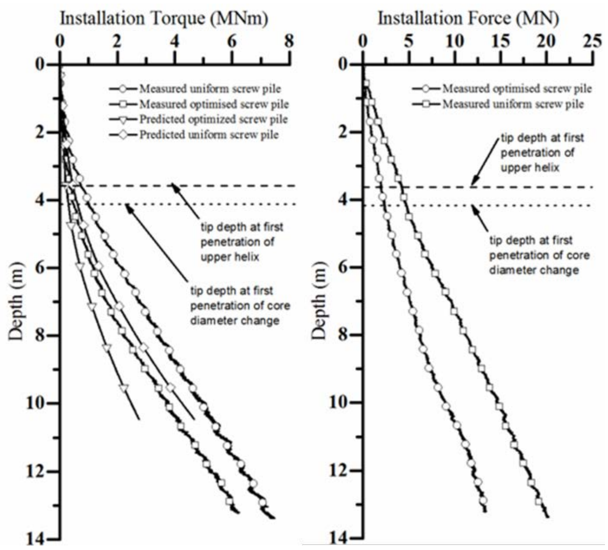

Figure 7 L) Vertical installation force and R) installation torque required for uniform and optimized screw pile designs.

2.2.1 Predicting installation requirements

Due to the significant size and surface area of the screw piles required for offshore deployment it is likely that significant torque (and possibly vertical force) installation will be required (Figure 7). In order to install these piles specialist plant will have to be developed with appropriate capabilities and at significant cost. Therefore, certainty over predicting installation requirements is necessary for offshore development.

Throughout the centrifuge works of Al-Baghdadi (2018) and Davidson et al. (2018a) cone penetration testing (CPT) has been undertaken in parallel with screw pile installation and load testing. CPT was adopted as this is the preferred offshore site investigation tool in sand and there are correlations with other common design parameters as well as direct methods of using CPT to determine in-service pile capacity. There are also examples of both analytical and CPT based predictions of screw pile torque requirements in the literature (Ghaly, and Hanna, 1991, Sakr, 2015, Gavin et al. 2013, Spagnoli, 2016). For example, equation 1 could be used for this but it would require an accurate prediction of in-service capacity and would be subject to the uncertainties in this approach as already discussed above.

Al-Baghdadi (2018) initially proposed an improved CPT based torque and vertical installation method that allowed for different geometry piles and multiple helices (previous methods had only incorporated a single helix). This was further corrected and improved by Davidson et al. (2018b) & Davidson et al. (2020). The torque which develops from the installation of a screw pile into sand is assumed to be created by the frictional resistance between the soil and the entire surface area of the pile. In terms of the proposed CPT-torque correlation method, the torque contribution from the upper surface of the helical plates(s) to the total torque is negligible and can be ignored. The torque from the shaft area of the core is calculated based upon the UWA 05 method (Lehane et al., 2005) where a stress drop index equal to the CPT friction ratio divided by the interface friction was used to compute the radial stress acting on the screw pile. This CPT prediction method as mentioned can deal with complicated pile geometry and the inclination of the screw pile helix, the pitch angle and the interface frictional properties. In a similar fashion based upon the UWA 05 method (Lehane et al., 2005) a CPT screw pile prediction method was defined to predict vertical installation force requirements for pitch matched installation. These methodologies are not given here due to space limitations and more detail can be found in Al-Baghdadi et al. (20017b), Al-Baghdadi (2018), Davidson et al. (2018b) & Davidson et al. (2020)

The results shown in Figure 8 highlight the ability of the proposed CPT methods to predict the installation torque for offshore geometry piles and that they offer better predictions than exiting insitu based techniques. Similar good performance of the prediction techniques was obtained when used for real case study sites. Comparison is only shown for single helix piles as although the method developed here can handle complex pile geometries existing techniques by others only work for single helix piles.

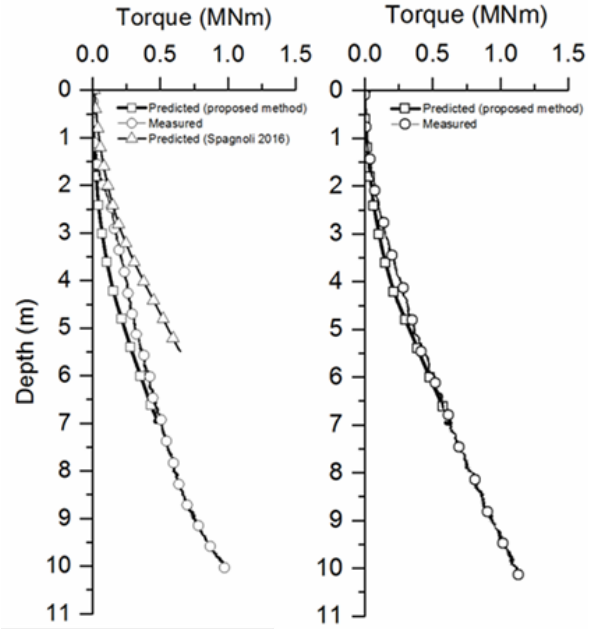

Figure 8 Predicted and measured prototype installation torque from centrifuge tests of: L) single helix screw pile; R) multi-helix (2 No.) screw pile. Symbol notation: square - predicted torque from the proposed method; triangle – predicted torque from (Spagnoli, 2016); circle – measured torque.

2.3 Other areas of development

2.3.1 Numerical techniques

Development in numerical techniques has focused on the use of Plaxis FEA and discrete element modelling. FE studies have been used to investigate the uplift failure mechanism and the effect of soil density and multiple or single helices as already mentioned and has been used to inform improved tensile capacity models as already discussed (Cerfontaine et al. 2019a). The other aim was to develop the use of FE such that as an industrially available and regular used approach it could be used in a non-specialized manner to simulate large deformation problems (without the need for less user friendly LDFE, MPM or DEM). A similar ethos was employed by Knappett et al. (2016) to allow FE to simulate CHD pile performance based upon the effect of installation seen in model tests with comparison to field study data.

The approach adopted for screw piles is outlined in Cerfontaine et al. (2019b) and is a push and replace or push and retain type methodology. In this approach a screw pile geometry is wished in place at some depth above the final installation position. It is then subjected to the vertical load measured in a parallel centrifuge test at the corresponding depth (or as could be predicted from the CPT based vertical load prediction method). The stress and strains associated with this loading are captured and retained for the next step of analysis which is repeated until the pile reaches the final penetration depth. The pile can then be loaded as it would be in-service under displacement control. The method also includes observed strain softening along the failure plane of the uplifting wedge.

Figure 9 and 10 show the potential for improvements in simulation based prediction of screw pile uplift capacity where informed attempts are made to incorporate installation effects. The results show a much better prediction of low displacement stiffness and general form of pile behavior. The figures also show investigation of whether or not uplift failure occurs as a straight cylinder or an uplifting wedge defined by the dilation angle. The results would suggest that the latter is more appropriate as previously found in FE simulations and by others undertaking work on uplift behavior of buried pipelines.

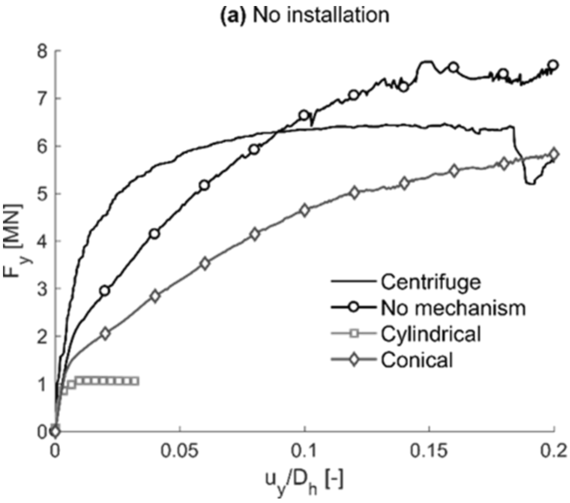

Figure 9, FE prediction of measured centrifuge screw pile test for a simple wished in place model.

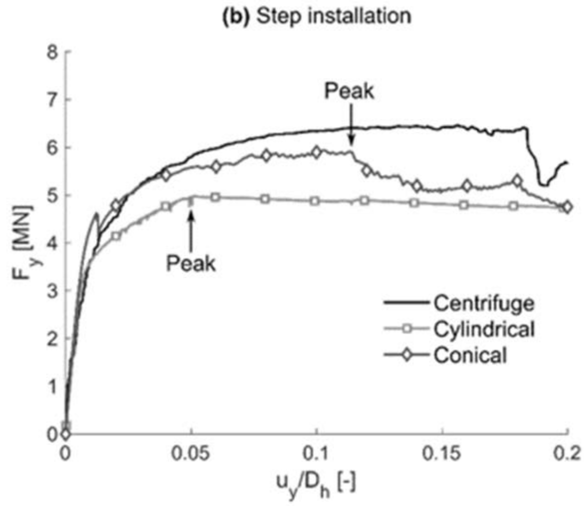

Figure 10, FE prediction of measured centrifuge screw pile test based upon simulations containing strategies to incorporate installation effects.

As well as utilizing FE with simulation of installation effects for screw pile modelling much work has been undertaken using discrete element modelling DEM (PFC 3D). Historically this approach may not have been seen as practical based upon the times required to create large enough soil beds or chambers for simulation and the general run time of events. This has been overcome with advances in soil bed preparation (Ciantia et al. 2018 & Sharif et al. 2019) using the Particle Refinement Method (PRM) and Periodic Boundary Replication Method (PBRM) and the reducing computational costs where a £2500-5000 GBP desk top work station can be adequate and allow simulations at speeds comparable to 3D FE.

The results of DEM simulation of screw pile loading and installation can be calibrated against similar centrifuge tests or in a commercial environment against actual triaxial tests or CPT tests where the same triaxial or CPT test can also be simulated in DEM and the parameters controlling the DEM simulation adjust to suit the laboratory or field measurements.

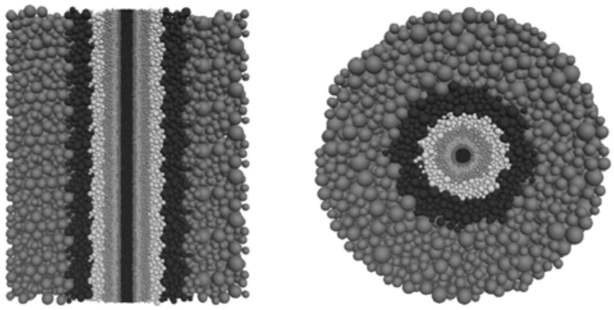

Figure 11 Example sample made using PRM and PBRM method, shading indicates different particle scaling applied to the PSD. L) Cross sectional view of sample, R) top view of sample

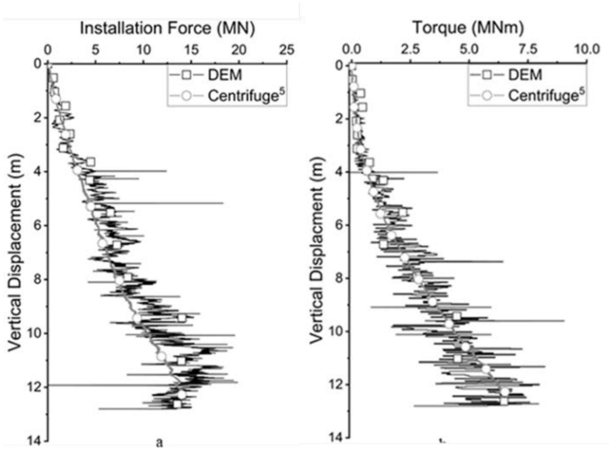

Figure 12 Comparison of DEM screw pile installation with measured centrifuge results.

The results in Figure 12 show the DEM simulation of installation of the optimised pile (Figure 6) compared to that measure in centrifuge testing. The consistency of the DEM simulation with the measured results is very good if not a little noisy. The noise itself in the main is due to the size of the balls used to optimize runtimes and could be reduced with smaller balls close to the pile at the expense of computational time.

The use of DEM in screw pile or displacement pile simulation shows great promise as results are fully repeatable (same soil chamber repeatedly used) and the geometry or the installation approach for the pile can easily be modified making it quicker than fabricating new piles for centrifuge testing.

3 FUTURE RESEARCH DIRECTION

Research with a view to bringing the industrial deployment of screw piles for offshore renewable energy deployment will continue at the University of Dundee (UoD). This will occur through on-going projects looking at the performance of screw piles in clays and recent industrial funding to accelerate the Technology Readiness Level (TRL) with a view to full scale or reduced scale demonstrator deployment in the near future. This forms part of a wider project using both centrifuge scaled model testing and DEM simulation to develop a variety of “Silent” piling techniques for offshore use (Huisman et al. 2020). Further information on these techniques can be seen by watching the videos via the following links:

Push-in piles:
https://go.hmc-heerema.com/visuals/1501810.80844-HE-136-333-20/
Helical piles:
https://go.hmc-heerema.com/visuals/1501810.80844-HE-136-333-03/

To date the work has focused on installation and requirements and monotonic in-service performance. The large torque and vertical compressive force required to install the piles needs to be reduced where possible through either geometry modification for example different tip geometries and open and closed piles. The work outlined in Huisman et al. (2020), Garcia Galindo et al. (2018) and Bradshaw et al. (2019) suggests that installation requirements can be reduced through over rotation or overflighting (i.e. ignoring the advice to install pitch matched or perfect installation). For example, Huisman et al. (2020) show from centrifuge testing that vertical installation forces can be reduced to zero by overflighting (or over rotating) although the effects on in-service compressive performance require further investigation.

The work at UOD to date has focused on in-service monotonic performance but it is acknowledged that further work is required with respect to cyclic performance although work has been done in this area as previously mentioned (Newgard et al. 2019, Schiavon et al. 2019). This previous work must be repeated for the pile geometries being developed for offshore use and with further focus on the potential for cyclic ratcheting through for instance DEM with varying particle sizes. The existing UoD centrifuge actuation rig will be upgraded to allow both displacement and stress-controlled loading to allow validation of DEM studies.

Further ongoing apparatus developments include the fabrication of a fully instrumented pile that measures both axial loads and bending moments at various points along its length (again for DEM validation). This has resulted in the need for classic slip rings to be used again local to the pile to get the many channels of data past the rotating connections. The other design change is that this pile and the connections to the loading rig are designed to be rotated in both directions such that decommissioning, or removal of screw piles can also be investigated.

Much of our recent work has been undertaken in partnership with the Durham University (DU) and the University of Southampton. DU have focused on developing new or refined computational techniques (Material Point Method, MPM) and applying them to the challenges of screw pile installation (Wang et al. 2019). The university of Southampton have been undertaking a series of field investigations in sand to validate the work at UoD and DU whilst creating an important case study data set on screw pile installation and in-service performance (Richards et al. 2019). Their work is also on-going.

4 SUMMARY AND CONCLUSIONS

The University of Dundee have been undertaking research since 2007 on a variety of screw piles. Initially these were cast insitu continuous helical displacement piles (CHD). This allowed equipment to be created that was later used to undertake undergraduate and MSc projects on steel screw piles normally used onshore for under-pinning and guyed supports. Due to their silent installation properties and the need for deeper water alternatives to monopiles it was decided to investigate upscaling of these pile types to allow deployment offshore.

This has been done through a variety of research studies using both physical modelling techniques and numerical approaches (FEA, DEM, MPM). The results to date have resulted in:

- CPT based methods for predicting installation requirements for complex geometry screw piles.
- Improved methods of predicting and designing both in-service tensile and compressive capacity for large screw pile geometries.
- Insights on how to optimized offshore screw piles and what optimized pile designs might look like.
- Development of the use of DEM for screw pile simulation.
- Identification of how screw pile installation requirements may be significantly reduced through different approaches to installation.

Although much has been achieved, further work is required to bring this foundation system to a higher technology readiness level for offshore deployment in the applications identified.

5 ACKNOWLEDGEMENTS

We would like to thank Roger Bullivant Limited (RBL) and particularly Jon Ball for their support, help and guidance throughout our many years of looking at piles. RBL continue support our work through sponsorship of current PhD student Yaseen Sharif. We would like to acknowledge the support of EPSRC for funding over many years that has contributed to our current level of understanding: EPSRC CASE for New Academics, EPSRC Supergen Windhub Call 2015: Grand Challenge project EP/N006054/1., EPSRC NPIF funded studentship with industry contribution – Screw piles in clay soils. More recently facilities and staff have been supported by the EU through LUPS/ERDF/2013/10/1/0075 to create the Scottish Marine Renewables Test Centre for Materials & Foundations (SMART), 2017, EU H2020 Marie SkŁodowska-Curie Actions Individual Fellowships SAFS – Development of Screw Anchors for Floating marine renewable energy System arrays incorporating anchor sharing. H2020-MSCA-IF-2016, Grant no. 753156 (08/17-07/19). We would also like to thank many colleagues, students, technicians and research partnerships (Durham University and the University of Southampton, Industry: Cathie Associates, SMD, RBL, InSitu SI, Lloyd's Register, Hereema Marine Contractors) that have contributed to the success of our ongoing work.

6 REFERENCES

Al-Baghdadi, T., Brown, M.J., Knappett, J.A. and Ishikura, R. 2015. Modelling of laterally loaded screw piles with large helical plates in sand*. In V. Meyer (eds) 3rd Int. Symp. on Frontiers in Offshore Geotechnics,* Oslo, Norway, 10 -12 June 2015. Taylor & Francis Group, London: 503-508.

Al-Baghdadi, T., Brown, M.J. and Knappett, J.A. 2016. Development of an inflight centrifuge screw pile installation and loading system. *In Thorel, L., Bretschneider, A., Blanc, M. & Escofier, S. (eds) 3rd European Conference on Physical Modelling in Geotechnics (Eurofuge 2016)*, Nantes, France. 1-3 June: 239-244.

Al-Baghdadi, T, Brown, M.J., Knappett, J.A. and Humaish, A. 2017a. Effects of vertical loading on lateral screw pile performance. *Proc. Inst. of Civil Engineers: Geotechnical Engineering Journal,* Vol 170, GE3: 259-272.

Al-Baghdadi, T, Brown, M.J., Davidson, C., Knappett, J., Brennan, A., Wang, L., Coombs, W.M., Augarde, C.E., Richards, D. and Blake, A. 2017b. CPT based design procedure for installation torque prediction for screw piles installed in sand. *8th Int. Conf. on Offshore Site Investigation & Geotechnics (SUT OSIG), 12-14th Sept.,* London, UK(1): 346-353.

Al-Baghdadi, T. 2018. *Screw piles as offshore foundations: Numerical and physical modelling*. PhD thesis, University of Dundee, Dundee, UK

Bradshaw, A.S., Zuelke, R., Hildebrandt, L., Robertson, T. and Mandujano, R. 2019 Physical modelling of a helical pile installed in sand under constant crowd. *Proceedings of the 1st International Symposium on Screw Piles for Energy Applications (ISSPEA). 27-*28th May. University of Dundee, Dundee, UK.: 109-115.

Brennan, A.J., Knappett, J.A., Brown, M.J., Bertalot, D., Loli, M. and Anastasopoulos, I. 2014. Dynamic centrifuge modelling facilities at the University of Dundee and their application to studying seismic case histories. *8th Int. Conf. On Physical Modelling in Geotechnics ICPMG'14*, Perth, Western Australia, 14-17th Jan: 227-233.

Caton, A. 2016. *Examining the behaviour of screw anchors under varying load inclinations*. MSc Thesis. University of Dundee. Dundee, UK.

Cerfontaine, B., Knappett, J.A., Brown, M.J. and Bradshaw, A.S. 2019a Effect of soil deformability on the failure mechanism of shallow plate or screw anchors in sand. *Computers and Geotechnics*. Vol. 109: 34-45.

Cerfontaine B, Brown M.J., Knappett J.A. and Davidson C. 2019b. Finite element modelling of the uplift behaviour of screw piles in sand. Proceedings of the *1st International Symposium on Screw Piles for Energy Applications (ISSPEA).* 27-28th May. University of Dundee, Dundee, UK: 69-75 https://doi.org/10.20933/100001123.

Cerfontaine, B., Knappett, J.A., Davidson, C., Brown, M.J., Brennan, A.J., Al-Baghdadi, T., Augarde, C., Coombs, W., Wang, L., Blake, A., Richards, D.J. & Ball, J.D. 2020. A Finite Element approach for determining the full load-displacement relationship of axially-loaded screw anchors, incorporating installation effects. *Canadian Geotechnical Journal*. Submitted for consideration.

Ciantia, M.O., Boschi, K., Shire, T. and, Emam, S. (2018) Numerical techniques for fast generation of large discrete-element models. *Proc Inst Civ Eng - Eng Comput Mech,*171(4):147–61.

Das, B.M. & Shukla, S.K. (2013*) Earth anchors*, J. Ross Publishing.

Davidson, C., Al-Baghdadi, T., Brown, M.J., Knappett, J., Brennan, Augarde, C.E., A., Wang, L., Coombs, W.M., Richards, D. and Blake, A. 2018a. Centrifuge modelling of optimised screw piles for offshore wind energy foundations. *Proc. 9th International Conference on Physical Modelling in Geotechnics (ICPMG 2018)*, 17-20th July, London, UK. Taylor & Francis Group, London, UK: 695–700.

Davidson, C., Al-Baghdadi, T., Brown, M.J., Knappett, J., Brennan, Augarde, C.E., A., Coombs, W.M., Wang, L., Richards, D., Blake, A. and Ball, J. (2018b) A modified CPT based installation torque prediction for large screw piles in sand. 4th International Symposium CPT'18 - Cone Penetration Testing. 21-22 June 2018, Delft, Netherlands. CRC Press. pp. 255-261.

Davidson, C., Brown, M.J., Cerfontaine, B., Knappett, J.A., Brennan, A.J., Al-Baghdadi, T., Augarde, C., Coombs, W., Wang, L., Blake, A., Richards, D.J. and Ball, J.D. 2020. Feasibility of screw piles for offshore jacket structures. *Geotechnique*. Submitted for consideration.

Fleming, K., Weltman, A., Randolph, M. and Elson, K. 2008. *Piling Engineering*, Taylor and Francis.

Gavin, K., Doherty, P. and Spagnoli, G. 2013. Prediction of the installation torque resistance of large diameter helical piles in dense sand. *Proceedings of 1st Int. Geotechnical Symposium of Helical Foundations*. Amherst, USA.

Garcia Gallindo, P., Davidson, C. and Brown, M.J. 2018. Installation behavior of open ended and closed ended piles with torque application*. Proceedings of the 1st International Conference on Press-in Engineering 2018*, 19-20th September, Kochi, Japan. International Press in Association, Japan: 379-386.

Ghaly, A. and Hanna, A. 1991. Experimental and theoretical studies on installation torque of screw anchors. *Canadian Geotechnical Journal*, 28: 353-364

Horvath, A. 2018. *Examining inclined installation of screw anchors scaled up for offshore renewable energy deployment*. MSc Thesis. University of Dundee. Dundee, UK.

Huisman, M., Ottolini, M., Brown, M.J., Sharif, Y. and Davidson, C. 2020. Silent deep foundation concepts: push-in and helical piles. *4th Int. Symp. on Frontiers in Offshore Geotechnics*. Austin, Texas, USA. 16 -19 August. Taylor & Francis Group, London. Submitted for consideration.

Jeffrey, J. 2012. *Investigating the performance of continuous helical displacement piles*. PhD thesis, University of Dundee, Dundee, UK.

Jeffrey, J., Brown, M.J., Knappett, J.A., Ball, J. and Caucis, K. 2016. CHD pile performance, Part I:

physical modelling. *Proc. Inst. of Civil Engineers: Geotechnical Engineering Journal,* 169(5): 421-435.
Karthigeyan, S. 2008. Numerical investigation of the effect of combined loading on the lateral response of piles in sand. *Challenges and Applications of Mathematical Modeling Techniques in Building Science and Technology (CAM2TBST).* Central Building Research Institute, Roorkee, India: 420–429.
Knappett, J.A., Brown, M.J., Brennan, A.J. and Hamilton, L. 2014. Optimising the compressive behaviour of screw piles in sand for marine renewable energy applications. *Int. Conf. On Piling & Deep Foundations, Stockholm, Sweden,* 21st-23rd May. Article #1904; publication #100 (IC-2014).
Knappett, J.A., Caucis, K., Brown, M.J., Jeffrey, J. and Ball, J. 2016. CHD pile performance, Part II: numerical modelling. *Proc. Inst. of Civil Engineers: Geotechnical Engineering Journal*, 169(5): 436-454.
Knappett, J., and Craig, R. F. 2019. *Craig's Soil Mechanics*. (9th ed.) Boca Raton, FL: CRC Press.
Koschinski, S. and Lüdemann, K. 2013. *Development of Noise Mitigation Measures in Offshore Wind Farm Construction 2013,* Report commissioned by the Federal Agency for Nature Conservation (Germany), (February), p. 102
Lehane, B. M., Schneider, J. A. and Xu, X. 2005. The UWA-05 method for prediction of axial capacity of driven piles in sand. *In Gourvenec, S. & Cassidy, M. (Eds.) Frontiers in Offshore Geotechnics*. Taylor & Francis.
Lutenegger, A. 2019. Screw piles and helical anchors – what we know and what we don't know: an academic perspective – 2019. *Proceedings of the 1st International Symposium on Screw Piles for Energy Applications (ISSPEA)*. 27-28th May. University of Dundee, Dundee, UK: 15-28.
Newgard, J.T., Mccartney, J.S., Schneider J.A. and Thompson D.J. 2019. Static and cyclic axial loading of single and multiplate helical anchors in sand. *Proceedings of the 1st International Symposium on Screw Piles for Energy Applications (ISSPEA)*. 27-28th May 2019. University of Dundee, Dundee, UK: 81-86.
Pavan Kumar, P.V., Patra, S. and Haldar, S. 2019. A critical review on design aspects of screw piles for renewable energy devices. *Proceedings of the 1st International Symposium on Screw Piles for Energy Applications (ISSPEA)*. 27-28th May. University of Dundee, Dundee, UK: 59-66.
Perko, H. A. 2009. *Helical piles: a practical guide to design and installation*, Hoboken, New Jersey, John Wiley & Sons.
Richards, D.J., Blake, A.P., White, D.J. Bittar, E.M. Lehane, B.M. 2019. Field tests assessing the installation performance of screw pile geometries optimised for offshore wind applications. *Proceedings of the 1st International Symposium on Screw Piles for Energy Applications (ISSPEA).* 27-28th May. University of Dundee, Dundee, UK: 47-54.
Sakr, M. 2010. Lateral resistance of high capacity helical piles – case study. *Proceedings of the 63rd Canadian Geotechnical and 6th Canadian Permafrost Conference*, Calgary, Alberta: 402–412.
Sakr, M. 2015. Relationship between installation torque and axial capacities of helical piles in cohesionless soils. *Canadian Geotechnical Journal*, 52: 747-759
Santos Filho, J.M.S.M., Silva Oliveira Morais, T. and Hollanda Cavalcanti Tsuha, C. 2014. A new experimental procedure to investigate the torque correlation factor of helical anchors. *Electronic Journal of Geotechnical Engineering (EJGE)*, 19 [2014], Bund. P: 3851-3864.
Schiavon, J.A., H.C. Tsuha, C. and Thorel, L. 2019. Behaviour of a single helix anchor in sand subjected to cyclic loading: Centrifuge modelling*. Proceedings of the XVI Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVI PCSMGE),* Cancun, Mexico, 17 – 20 November: 493-500.
Spagnoli, G. 2016. A CPT-based model to predict the installation torque of helical piles in sand. *Marine Georesources & Geotechnology:* 1-8.
Wang, L., Coombs, W.M., Augarde, C.E., Cortis, M., Charlton, T., Brown, M.J., Knappett, J., Brennan, A., Davidson, C., Richards, D. & Blake, A. 2019. On the use of domain-based material point methods for problems involving large distortion. *Computer Methods in Applied Mechanics and Engineering J.* 355: 1003-1025.
Zhang, D.Y. 1999. *Predicting capacity of helical screw piles in Alberta soils*. MSc thesis, University of Alberta, Edmonton, Canada.